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IDENTIFICATION OF AIR TRAFFIC CONTROL SECTORS WITH COMMON STRUCTURAL FEATURES

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In order to identify sectors supporting a minimum differences approach to generic airspace, traffic patterns in 360 high-altitude sectors were examined for common structural features. These structural features are used as the basis for two approaches to classifying current air traffic control sectors into groups which are expected to be similar to each other, and hence a basis for near-term deployment of generic airspace. The first classification approach is a holistic approach, based on emergent sector-wide traffic patterns in order to identify groups of sectors with shared structural features. The second, a decompositional classification approach, proposes using basic structural features (e.g. flows, merges, crosses) as building blocks, and classifies sectors based on combinations of those features. Initial classification results are presented for the holistic approach, and challenges and key steps are presented for the decompositional approach.

Introduction

In the United States the typical Certified Professional Controller (CPC) will maintain qualification on only a limited number of sectors (typically 5-7) within an area of specialization (Histon and Hansman, 2008). In order to move to and control sectors within a different area of specialization, significant and timely retraining activities are required. Consequently, staffing flexibility is limited and it is difficult for the Federal Aviation Authority (FAA) to respond to seasonal variations in staffing demands. Developing generic airspace, or airspace that is similar enough that no or minimal retraining is required to transfer a qualified controller between sectors is a possible means to address this challenge.

Analysis by MITRE has identified high altitude airspace as having the least number of airspace knowledge items (Levin, 2007). This, combined with the more homogenous mix of aircraft types and capabilities, makes high-altitude airspace attractive for an initial investigation of the potential of generic airspace. One way to deploy generic high-altitude airspace is to create sets of standardized or similar sectors. In order to create such set, though, it first must be determined what it means for a sector to be similar to others. The greater the standardization, the greater the flexibility; however, this comes at the cost of locally adapted sector-specific procedures and operations that provide locally tailored and more efficient operations. To balance these competing pressures, a minimal differences training approach to the development of generic airspace is being investigated. In this approach, classes of sectors are identified that could be made similar, but not necessarily identical, and controllers would then receive short targeted training on the relevant differences between the generic sectors in a particular class. This approach builds on our previous work which has identified the importance of supporting easily transferable mental models and abstractions in air traffic control (ATC) (Histon and Hansman, 2008).

To assess the potential of the minimal differences training approach, this paper presents a National Airspace System (NAS)-wide analysis of the similarity of existing high-altitude sectors. The analysis examines sectors from the perspective of structure, or “the physical and information elements that organize and arrange the air traffic control environment” (Histon and Hansman, 2008). First, key structural features that are thought to play a significant role in defining groups of similar sectors were identified. These structural features were then used as a basis for two classification methods for identifying groups of similar sectors. A holistic classification method, based on sector wide traffic patterns, is illustrated and preliminary classification of sectors is presented. A second method, based on explicitly decomposing sectors using the identified structural features is then presented.

Generic Airspace and Previous Work on Airspace Classifications

Interest in generic airspace has been driven by both experimental and operational considerations. Many experiments investigating new ATC operational concepts have been performed using generic sectors. Typically, a generic high-altitude sector is used to ensure that participants have similar backgrounds and previous experience with the airspace in the experiment, to avoid confounds associated with previous experience. These sectors are specifically designed to replicate the characteristics of a typical high-altitude sector, and to facilitate rapid learning for experimental participants (Guttman et al., 1995; Guttman and Stein, 1997). Generic sectors are also envisioned as part of new high-altitude airspace concepts, such as the Dynamic Airspace Super Sectors (Alipio et al., 2003).

However, classification and identification of similarities between existing airspace sectors has not been extensively studied. Christien (2003) used a Complexity Index (CI) as a basis for establishing common groups of sectors in European airspace. Much more research has focused on identifying complexity factors (Laudeman et al. 1998). Typical complexity factors include: aircraft density, the proportion of aircraft changing altitudes, sector size, and sector shape (comprehensive complexity factors lists can be found in reviews by Hilburn, 2004; Majumdar and Ochieng, 2001). Kopardekar and Magyarits (2003) found significant differences in the relative importance of complexity factors between en route facilities in the United States.

The breadth of potential complexity factors introduces the need to determine how the factors can be combined. Previous approaches have used weighted averages of identified factors to produce an overall complexity index (e.g. Kopardekar and Magyarits 2003, Laudeman et al. 1998). Other approaches have used algorithmic methods based on cluster identification techniques; groups of sectors (clusters) are identified by recursive splitting until the homogeneity of the resulting groups satisfy a pre-determined threshold (Christien, 2003).

These approaches, however, do not explicitly examine the potential of identifying common groups of sectors that would require reduced or minimal training for a controller to easily move amongst them. Structure has been shown to play an important role in controller cognitive complexity (Histon and Hansman, 2008) and is a useful perspective from which to identify similar sectors.

Approach

In order to identify key structural features and common groups of sectors, radar track data, collected through the Enhanced Traffic Management System (ETMS), were analyzed for two seven day periods (07/13/2009-07/19/2009 and 9/21/2009-9/27/2009). Radar tracks were plotted for flights that spent at least 10 minutes inside each high-altitude sector. As a first step, the radar track maps were reviewed for key structural patterns by manually going through the 360 high-altitude NAS-wide sector radar-track maps. After identifying several key structural patterns, these patterns were used as the basis for two approaches for classifying sectors into common groups. This classification exercise was first done by examining radar-track maps both on screen and using printed cards. Printing radar-track maps as mini-cards allowed easy physical maneuvering of the cards, which allowed quick grouping/de-grouping as different classification approaches were explored, similar to card-sorting techniques used in feature / requirement classification techniques used in design fields (Lafrenière et al., 2000).

Structural Features

To identify sector-specific elements and procedures that need to be similar and those that could be different in generic sectors, radar track maps depicting current sector operations were reviewed for key common structural features and recurring patterns. From this review, five key patterns were identified; Patterns 1 and 2 are consistent with previously reported structural patterns (e.g. Histon and Hansman, 2008) and are only briefly described.

Pattern 1 - Standard Flows. In most sectors, there are one or more distinct standard flows (Figure 1). Standard flows are the foundation for simplifying abstractions used by controllers to reduce cognitive complexity (Histon and Hansman, 2008). Hence, commonalities in the standard flows between sectors are thought to be important factor for identifying similar sectors.

Pattern 2 - Critical Points. Another key feature identified in multiple sectors was the presence of critical points, where flows cross, merges, and/or split (Figure 2). The relative location of the critical points, especially with respect to each other and sector boundaries, as well as the type (e.g. merge point vs. crossing point) can significantly impact cognitive complexity (Histon and Hansman, 2008; Hilburn, 2004). Similar to standard flows, critical points also support simplifying abstractions and are important considerations for identifying similar sectors.

Pattern 3 - Flow Trajectory Change Points. New structural features were identified in the review. Trajectory change points associated with flows (Figure 3) typically occur due to special conditions/restrictions such as keeping the flow within the lateral and/or vertical boundaries of the sector. The location of trajectory change points relative to other flows and the sector boundary is an important consideration for assessing sector similarity.

Pattern 4 - Vertical Handoffs. The radar track analysis also identified a key feature associated with aircraft being handed off and transitioning into or out of sectors vertically. In Figure 4, two flows can be seen terminating in the middle of the sector. The locations of the vertical handoffs, and their relationship with other flows in the sector (e.g. climbing or descending below a crossing flow) will likely affect how similar these characteristics need to be in order for two sectors to be considered similar.

Pattern 5 - Common Maneuvering Patterns. Two common maneuver patterns were also identified: the race-track holding pattern illustrated in Figure 5, and the path stretching pattern illustrated in Figure 6. Both of these features require free maneuvering airspace to be present in the sector. The location in the sector, and how it interacts with other elements such as military airspace, will likely affect how similar these features need to be in order for two sectors to be considered similar.

Classification Approaches

The identified structural features provide a basis for identifying potential generic sectors. Sectors with similar structural features support similar simplifying abstractions, and have similar types of knowledge associated with them. These structural similarities should thus support the minimal differences approach to generic airspace. Two distinct approaches to identifying sets of sectors with common structural properties have been developed. The first, a holistic approach, is based on the overall structural appearance of a sector, without explicit accounting for individual structural features. The second, a decompositional approach, uses individual structural features as building blocks and explicitly accounts for combinations of structural features to classify sectors into common sets.

Holistic Classification Approach

The holistic approach identifies similar sectors based on the overall structural features. The same radar traffic maps used to identify structural features were used to categorize the 360 high-altitude sectors based on

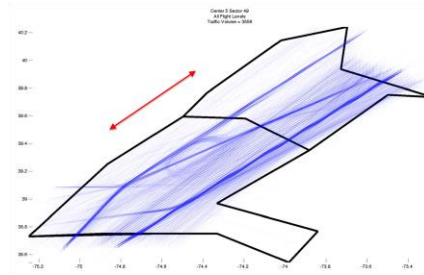


Figure 1. Standard flow

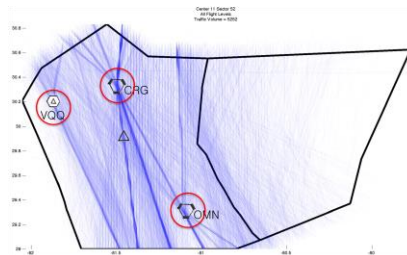


Figure 2. Critical points

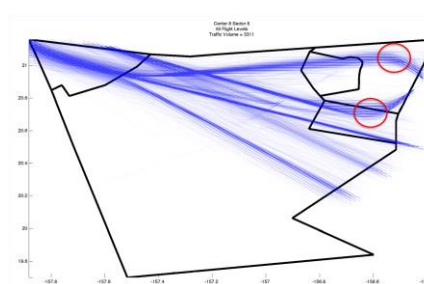


Figure 3. Flow trajectory change points

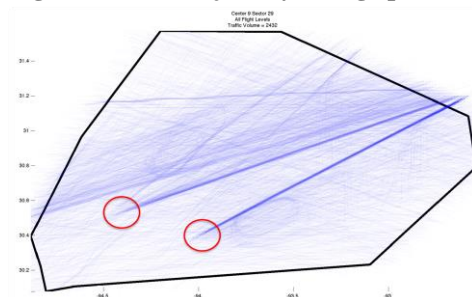


Figure 4. Vertical handoffs

common patterns in the number and interactions between flows and perceived density of the flows. Each sector was classified into only one class. Table 1 shows the frequency of sectors in each of the 16 sector classes. Example radar traffic maps for two classes are shown in Figure 7. The value in the centre of each classification cell in Table 1 represents

the percentage of sectors categorized into that class. The top 12 classes in the table represent different configurations of number and intensity of flows and non-standard flow traffic. Approximately 57% of the 360 NAS-wide high-altitude sectors were classified into these 12 classes.

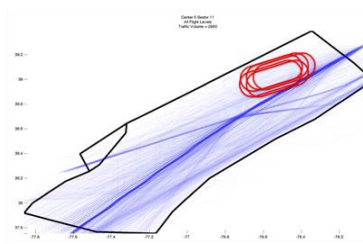


Figure 5. Holding pattern

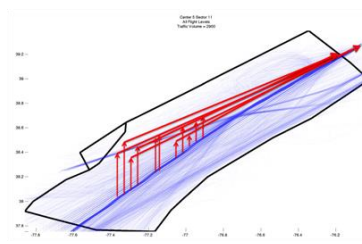


Figure 6. Path stretching pattern

Table 1. Visual and Canonical Guide for the Holistic Classification Approach

	Moderately Concentrated flows	Heavily concentrated flows	Heavily concentrated flows with densely distributed traffic in the background	
Single flow	4%	2%	7%	
Crosses	0%	6%	4%	
Merges/splits	2%	13%	6%	
Parallel flows	6%	6%	2%	
	Almost no traffic	Very light traffic	Complex traffic with moderately concentrated flows	Complex traffic with heavily concentrated flows
Others	13%	7%	9%	13%

Not all sectors had structural features that cleanly mapped into these 12 classes. Four additional classes listed under “Others” in Table 1, were used for sectors with unique structural features. These sets are distinguished by the density of background (non-standard) traffic and the density of the primary flows. 13% of sectors had extremely low traffic counts and 7% of sectors had no dominant structural features with the traffic spread out evenly throughout a larger area of a sector rather than forming a concentrated flow as a route. 22% of sectors were composed of multiple dominant structural features (e.g. two crosses with a merge and a parallel flow). These sectors were classified as belonging to sets with *complex traffic with moderately or heavily concentrated flows*.

Several challenges were identified in using the holistic approach to classification. No attempt was made to account for altitude differences in aircraft trajectories. Including altitude distinctions would lead to additional classes being identified; features such as crosses would have different training implications if they are generated by traffic at varied and procedurally segregated altitudes. The representations used did not distinguish between directions of flight, making it difficult to definitively distinguish between merges and splits; other contextual cues can be used, but for the purpose of this preliminary analysis a single class was identified. Given the obvious differences between

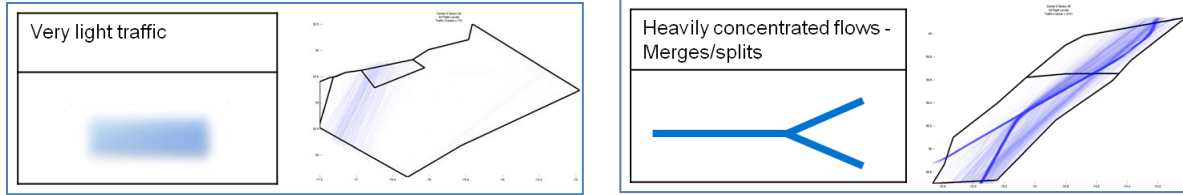


Figure 7. Example radar track maps: “Others – very light traffic” (left), “Merge / Split with heavily concentrated flows” (right).

merge and split operations, additional classes should be identified. Finally, the analysis was conducted using raw sector definitions; operations dictate that sectors are routinely combined during different parts of the day.

Nevertheless, Table 1 represents an initial break-out of the types of traffic patterns, and preliminary estimates of the relative frequency, that can be found across sectors in the NAS. The classes that are identified provide a basis for identifying groups of sectors that are expected to be similar enough to support a minimal differences approach to training in order to support controller qualification across the sectors in the class.

The Decompositional Classification Approach

Two shortcomings with the holistic approach motivated consideration of alternative approaches. First, the classes identified do not explicitly include the effects of key structural features such as the presence of standard maneuvering patterns. In addition, over 20% of sectors were classified as “complex traffic” sectors; however, there may be important opportunities for generic airspace sectors based on similarities between sectors within this class.

To address these challenges, a decompositional classification approach is being developed. In this approach, sectors are decomposed into elemental structural features. Similar sectors are identified based on the patterns of combinations of the elemental features. Examples of elemental features are shown in Figure 8: a crossing flow, a merge, parallel flows, a flow turn point, and a standard holding pattern. In Figure 9 three elemental features, a crossing flow, merge/split, and a holding pattern are identified in an example sector.



Figure 8. Examples of elemental structural features for the decompositional classification approach

In order to identify classes of similar sectors, combinations of these elemental features are added together using a notional sector algebra (Figure 9). This research is in a preliminary stage and several techniques are currently being investigated. The simplest is based on using a weighted combination of features, similar to the complexity based classification described by Christien (2003). Weights for elemental features in Figure 8 can be estimated based on their relative importance (e.g. cross assigned weight of “1” unit, a hold a weight of “2” units etc...) and then a Structure Score determined from the weighted sum of elements in each sector. Classes of sectors can then be determined by grouping sectors with similar Structure Scores. This has the advantage of simplicity and consistency with previous methods, but also loses much of the information gained by explicitly decomposing into individual elements. More sophisticated techniques, based on multi-dimensional clustering techniques and other formulations of multi-class classification algorithms are also being investigated.

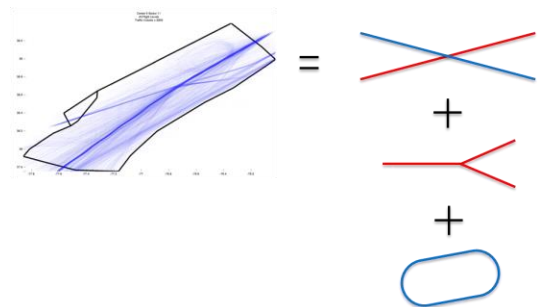


Figure 9. Elemental features in a sector (decompositional classification approach).

Whichever technique is used to aggregate the individual elements, there are several key challenges. The

relevant elemental features to be used in the decomposition must be identified. Ideally these should form a mutually exclusive set, however, there will be some overlap as some structural features (standard flows) are integral parts of other structural features (crossing points). The relative importance of a structural feature for similarity may also be dependent on the spatial relationship with other structural features; in addition to number of features, relative distances, intensity, and frequency of use may need to be included as part of the decomposition.

Summary

Radar track data for 360 high-altitude sectors were used to identify five key structural features; similarities in structural features provide a basis for identifying classes of generic sectors. Similarities between sectors in the same class would support a “minimal differences training” approach to the deployment of generic airspace. Two distinct methods of using structural features to classify sectors were presented. The holistic approach, based on assessing the overall structural appearance of a sector, was used to identify 16 classes of high-altitude sectors. The second, decompositional, approach was proposed as the basis for comparative analyses of structural features of the sectors. The identification of classes of sectors with similar structure provides a basis for assessing the potential of near-term deployment of generic airspace. Having identified classes of sectors, future work will be further refining the classes, and using human-in-the-loop experiments to verify the relevance of the identified differences.

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